INFLUENCE OF PRELOADING ON THE CONCRETE EDGE FAILURE OF SINGLE STUD ANCHOR AFTER FIRE EXPOSURE

EINFLUSS DER VORBELASTUNG AUF DEN BETONKANTENBRUCH VON KOPFBOLZEN NACH BRANDEINWIRKUNG

Joško Ožbolt, Luka Lacković, Kaipei Tian

Institute of Construction Materials, University of Stuttgart

SUMMARY

In the present numerical study, the influence of the preloading of anchors on the residual concrete edge failure capacity after fire exposure has been investigated. Single-headed stud anchor is exposed to the various fire durations and loaded in shear, perpendicular and towards the free edge of the concrete member up to failure, in both hot and cold state (after cooling). The influence of different geometry configurations and initial conditions such as the edge distance, embedment depth, anchor diameter and duration of fire on the load-bearing behavior of anchors was investigated. The standard ISO 834 fire curve with fire durations of 15, 30, 60 and 90 min was employed in the simulations. It is shown that the influence of preloading has a significant impact on the residual load-bearing concrete edge capacity of the concrete.

ZUSAMMENFASSUNG

In der vorliegenden numerischen Studie wurde der Einfluss der Vorbelastung von Einzelkopfbolzen auf den Kantenbruch nach Brandbeanspruchung untersucht. Der Kopfbolzen wird zuerst den verschiedenen Branddauern ausgesetzt und nach der Brandbelastung, sowohl im heißen als auch im kalten Zustand (nach Abkühlung), quer in die Richtung der freien Kante des Betonbauteils bis zum Bruch belastet. Der Einfluss der Geometrie (Randabstand, Verankerungstiefe, Bolzendurchmesser) und Branddauer auf das Tragverhalten von Ankern wurde untersucht. In den Simulationen wird die Standard-Brandkurve nach ISO 834 mit Branddauern von 15, 30, 60 und 90 min verwendet. Es zeigt sich, dass die Vorbelastung einen relativ starken Einfluss auf den Betonkantenbruch nach der Brandbelastung aufweist.

1. INTRODUCITON

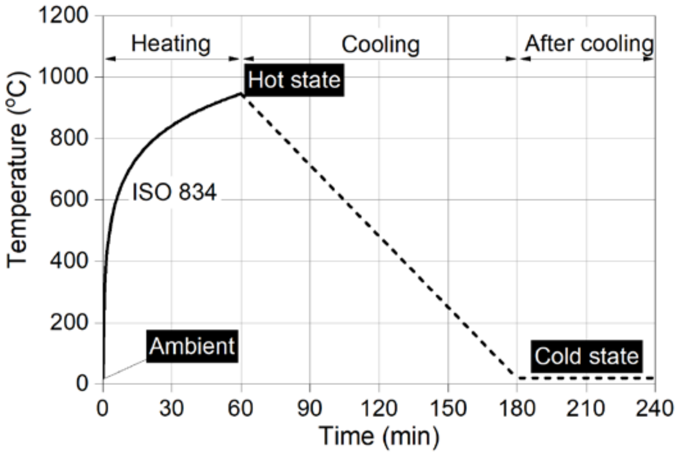
In the field of modern construction technology, it is often necessary to economically transfer loads in reinforced concrete structures using fasteners [1]. The behavior of fasteners has already been investigated in detail for environmental temperatures that are common in engineering practice [2-6]. However, their behavior changes significantly at high temperatures, such as those that can occur in case of fire [7-12]. The decrease in the mechanical properties of concrete and steel due to thermally induced damage causes a decrease of the load-bearing capacity of fasteners and a significant increase of deformations. Moreover, thermally induced strains and the associated constraint stresses can also have a strong influence on the resistance of fasteners [12].

Recent experimental studies [10-12] gave us a good insight into the behavior of fasteners exposed to different fire durations and subsequently loaded in shear towards the free edge of concrete. The tests were here used for calibration and verification of an existing thermo-mechanical model, which was previously implemented into a 3D finite element (FE) code [13-15]. After the model was calibrated and validated, extensive numerical studies for a single fastener load in shear close to edge were performed to investigate the influence of high temperature on its behavior. The studies were carried out for both, so-called hot and cold state. It was found that the most critical situation is the cold state. Namely, due to the cooling down the concrete member additional damage of concrete is generated, which leads to further degradation of residual resistance of fasteners previously exposed to fire. Due to the difficulties in designing experimental tests for preloaded fasteners exposed to fire, almost all available experimental investigations were carried out without preloading. However, since in the engineering practice almost all fasteners are preloaded, the question arises as to how the preloading influences the residual shear failure capacity of anchors close to the edge after fire exposure. Therefore, the numerical investigations were carried out for a single-headed stud anchor preloaded with design load according to Eurocode 2. In order to demonstrate that the used 3D FE code, which is based on the thermo-mechanical microplane model for concrete, is able to realistically replicate the response of a single anchor for concrete edge failure after fire exposure, the numerical results for fasteners without preloading are first compared with the available test data. Subsequently, the numerical parametric study was performed. Finally, the numerical results, for the hot and cold state, are presented and discussed.

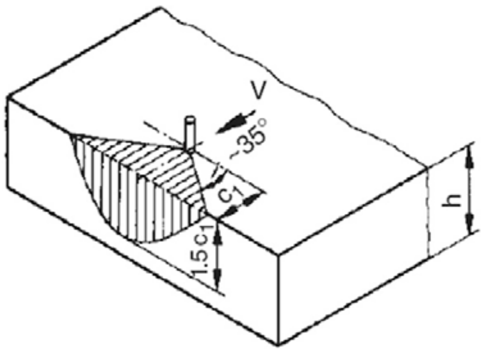
2. GEOMETRY AND NUMERICAL PROPERTIES

The geometry investigated in the numerical parametric study was taken from the recent experimental study [12]. The tested configuration is a single-headed stud anchor loaded in shear perpendicular to the edge (see Fig. 1). In the experiments, the concrete slab was heated from two sides (Fig. 1c) according to ISO 834 fire curve [16] (Fig. 1a) and then naturally cooled down to the environmental temperature (T = 20°C). Subsequently, the fastener was loaded in shear (cold state) up to failure. As already mentioned, the experiments were carried out for fastenings without preloading and only for the cold state.

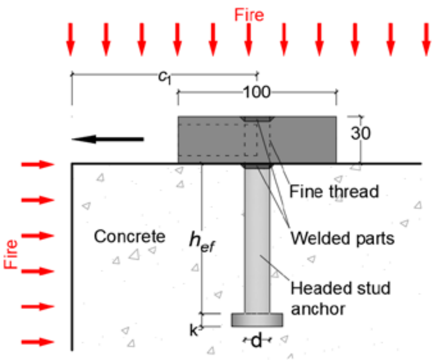
(a)



(b)



(c)



(d)

Fig. 1: (a) Heating curve according to ISO 834, (b) idealized shape of typical concrete failure body, (c) and (d) example of a single headed stud anchor in the fire test [12]

The following geometrical parameters were varied: (1) edge distance c_1 = 75, 100 and 150 mm; (2) anchorage embedment depth h_{ef} = 75 and 95 mm, anchor bolt diameter d = 16 and 25 mm (Fig. 1b). The simulations are carried out for concrete class C20/25. In order to exclude the failure of steel, it was assumed that steel is linear-elastic, i.e. heating of steel does not affect its mechanical properties. Due to a considerable quantity of simulations, the parametric study was not carried out for all possible combinations of the above parameters (geometry, fire load and mechanical load).

3. NUMERICAL ANALYSIS

3.1 GEOMETRY, MATERIAL PROPERTIES AND FE MODELS

In the 3D FE simulations as the constitutive law for concrete, the thermo-mechanical microplane model for concrete is used [13-15]. The finite element discretization (see Fig. 2) is performed according to the geometry and boundary conditions from the experimental tests [12] by employing 4-node constant strain solid finite elements. The connection between steel and concrete is performed by using contact elements that can transfer only compressive contact forces. To assure mesh size-independent results, the regularization based on the crack band method is used [17]. The properties of concrete and steel employed in the analysis are specified in Tab. 1. The temperature-dependent thermal properties of concrete and steel are taken according to Eurocode 2 EN 1992-1-2: 2004 Part 1-2 [18]. In all simulations, one symmetry plane was utilized (see Fig. 2).

Table 1: Material properties used in the simulations

Material	Young's modulus (GPa)	Poisson's ratio	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Fracture energy (J/m^2)	Heat conductivity (W/mK)	Heat capacity (J/kgK)	Mass density (kg/m^3)
Concrete C20/25	27	0.18	12	1.6	30	1.33	900	2300
Steel 1.4828	200	0.33	-	550-750	-	18.00	500	7900

The fire load was enforced by heating the environment (air) temperature according to the standard ISO 834 curve. The fire exposure times were varied from t = 0 (reference case) to 15, 30, 60 and 90 min. The fire was applied on two sides of the concrete specimen (see Fig. 2a). The preloading (shear service load according to Eurocode 2, see Tab. 2) was applied perpendicular and into the direction of the free edge. The shear resistance of fasteners was calculated for both, hot and cold state. In the hot state, the displacement control was applied on the fastener immediately after heating, as opposed to the cold state, where the fastener was first naturally cooled down to the room temperature (see Fig. 2b). The summary of simulated cases for the cold and hot state with and without preloading is given in Tab. 2 (hatched block).

Table 2: Summary of the simulated cases (units in [mm])

Edge distance	Embedment depth	Anchor diameter *d*		Preloading [kN]	
c_1	h_{ef}	*d*=16	*d*=25	*d*=16	*d*=25
75	75	-	+	-	7,56
	95	-	+	-	8,02
100	75	-	+	-	10,93
	95	+	+	10,71	11,52
150	75	-	+	-	18,6
	95	-	+	-	19,46

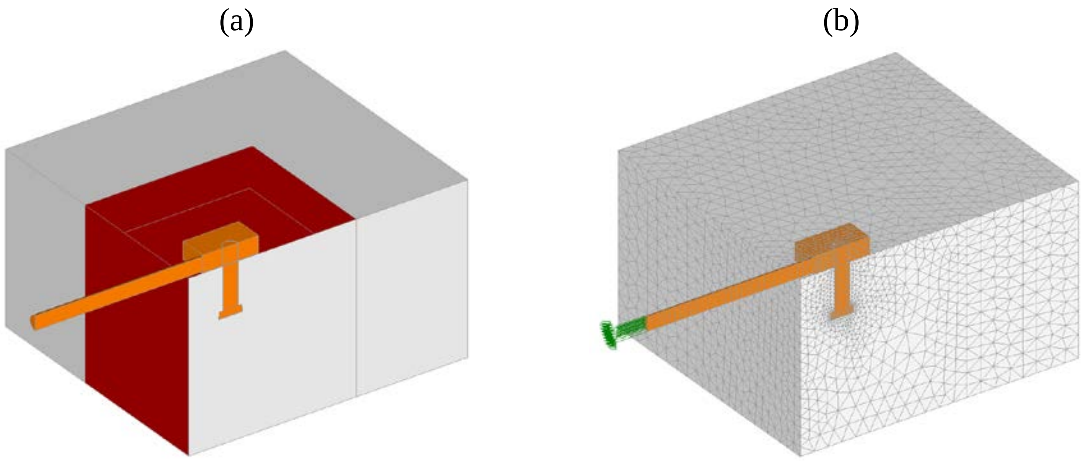


Fig. 2: Single headed stud anchor at the edge: (a) Two-sided fire exposure according to ISO-834 and (b) FE discretization (one symmetry plane)

3.2 VERIFICATION OF THE MODEL

To confirm that the employed thermo-mechanical model is able to realistically predict the behavior and resistance of fasteners after fire, the results of recently performed experimental tests are compared against the corresponding numerical results. As an example, only the results for a single anchor without preloading are here provided. The results are given for the cold state, for t = 0, 15 and 60 min of fire duration (c_1 = 75, 100 and 150 mm, h_{ef} = 95 mm and d = 25 mm, concrete C20/25).

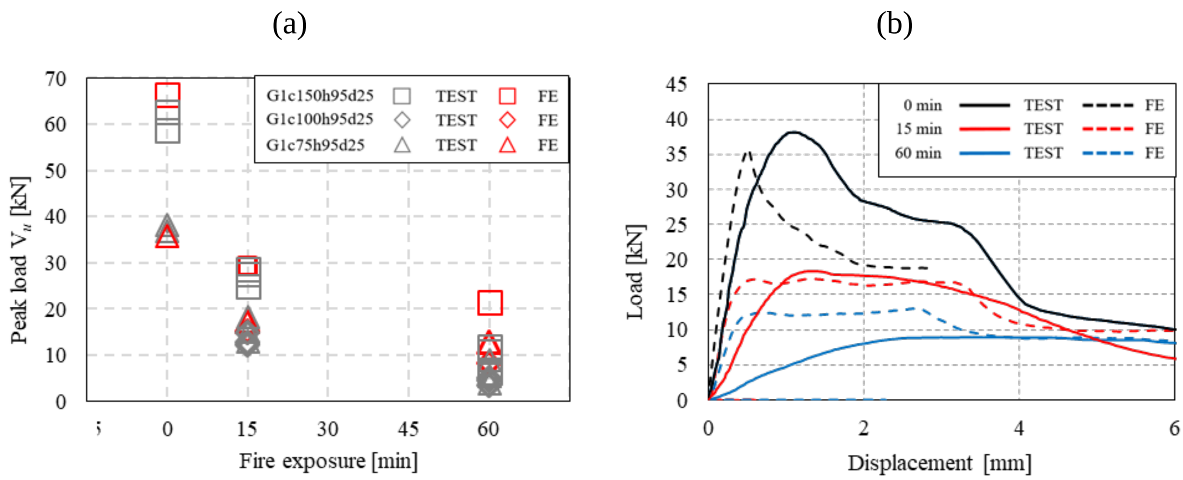


Fig. 3: Comparison between experimental and numerical results: (a) Resistance as a function of fire exposure and (b) Load-displacement curves for a single anchor

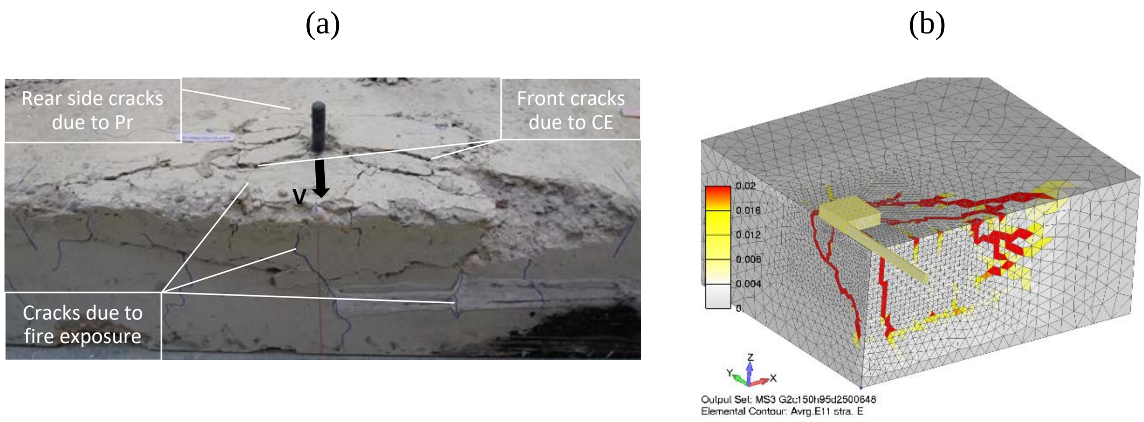


Fig. 4: Typical failure mode observed in the experiment [12] (a) and simulation (b)

As can be seen from Fig. 3a, the experimentally and numerically obtained results show for all anchor configurations strong degradation of shear resistance as a function of fire duration. Fig. 3b shows the measured and computed load-displacement curves for a single anchor. It can be seen that with an increase in fire duration the response becomes more ductile. The initial stiffness observed in the simulations is higher than in the experiment. The main reasons are local damage effects that cannot be properly accounted for in the macroscopic FE analysis. The typical failure modes are compared in Fig. 4. Since one symmetry plane was utilized, only a half of the model is depicted in Fig. 4b. Dark zones represent the maximum principal strains which correspond to the crack width equal or greater than 0.10 mm. Despite of high complexity of the problem, Figs. 3 and 4 confirm that the employed 3D FE thermo-mechanical model is able to reasonably well replicate temperature-dependent failure of anchors loaded in shear against the free edge of the concrete member.

3.3 PARAMETRIC STUDY

The typical load-displacement (L-D) curves of a single anchor (h_{ef} = 95 mm, c_1 = 75 mm, d = 25 mm) with and without preloading, in hot and cold state, are shown in Fig. 5. It is evident that with the increase of fire exposure, the load-bearing capacity decreases and ductility increases. This applies to both cold and hot conditions, with and without preloading of anchors. Furthermore, the reduction of resistance is higher for the cold state than for the hot state. Comparing the L-D curves, it can be seen that the fasteners with preloading show a greater decrease in load-bearing capacity as a result of the fire exposure. For longer fire exposures ($t \geq 60$ min), the load immediately after the application of displacement of anchor reduces and the resistance becomes smaller than the applied service load. This means that the pre-loaded fastener fails during the fire exposure, i.e. the residual load-bearing capacity is smaller than the service load. Note that during temperature exposure (heating and cooling) the analysis is carried out by the load control of the fasteners. The employed numerical procedure is not able to account for the descending part of the L-D curve, i.e. after reaching the peak resistance the equilibrium is not assured. However, since after thermal analysis the fasteners are loaded by displacement control, the equilibrium between external load and internal forces is again established with the consequence that the resulting load (the highest value of the L-D post-peak response shown in Fig. 5) actually represents the residual resistance, i.e. the load at which the fastener fails as a consequence of the preloading and thermally induced damage. In the experimental tests, this would take place during the thermal loading of fasteners (heating or cooling).

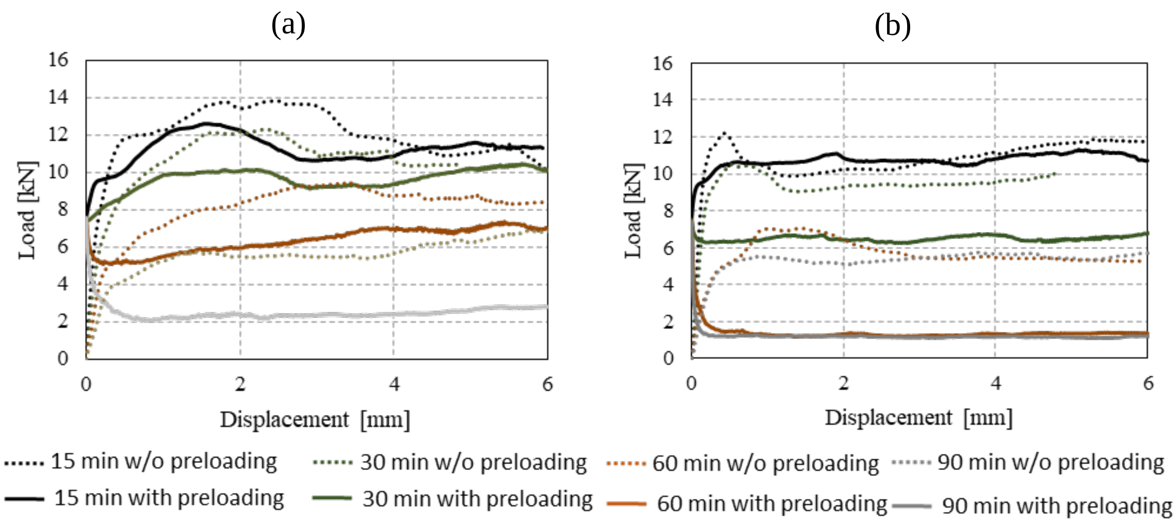


Fig. 5: L-D curves for c_1 = 75 mm, h_{ef} = 75 and d = 25 mm with preloading (solid) and without preloading: (a) warm condition; (b) cold condition

Fig. 6 shows the decrease of the resistance for two typical cases as a function of fire duration. It can be observed from Fig. 7 that, as in the tests [12], the strongest relative decrease of load-bearing capacity takes place in the first 15 minutes. It can also be observed that the decrease in load-bearing capacity is for most cases greater in the cold state than in the hot state. As already reported [12], the reason for this is the fact that the concrete is additionally damaged by the cooling process. Furthermore, it is also evident that the preloading has a relatively strong influence on the residual load-bearing capacity of fasteners.

(a) (b)

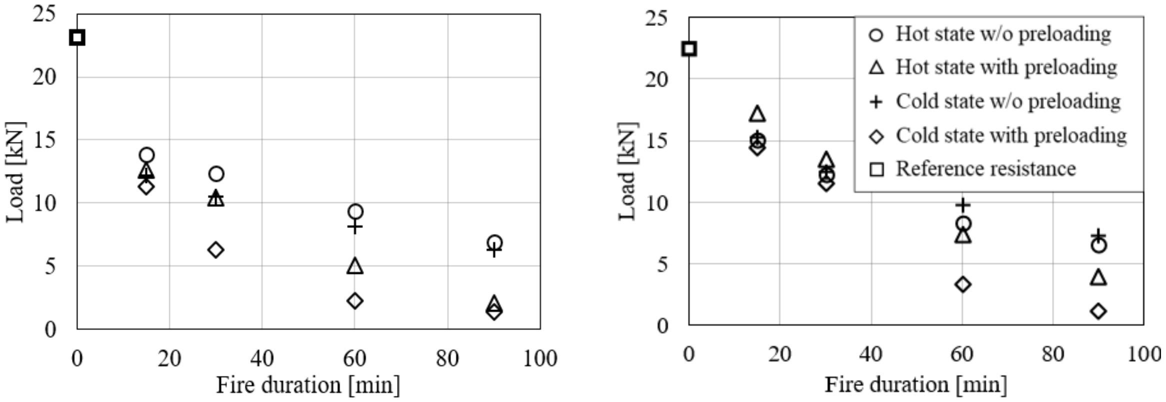


Fig. 6: The load capacity reduction as a function of fire duration for: (a) c_1 = 75 mm, h_{ef} =75 and d = 25 mm and (b) c_1 = 75 mm, h_{ef} = 95 und d = 25 mm

(a) (b)

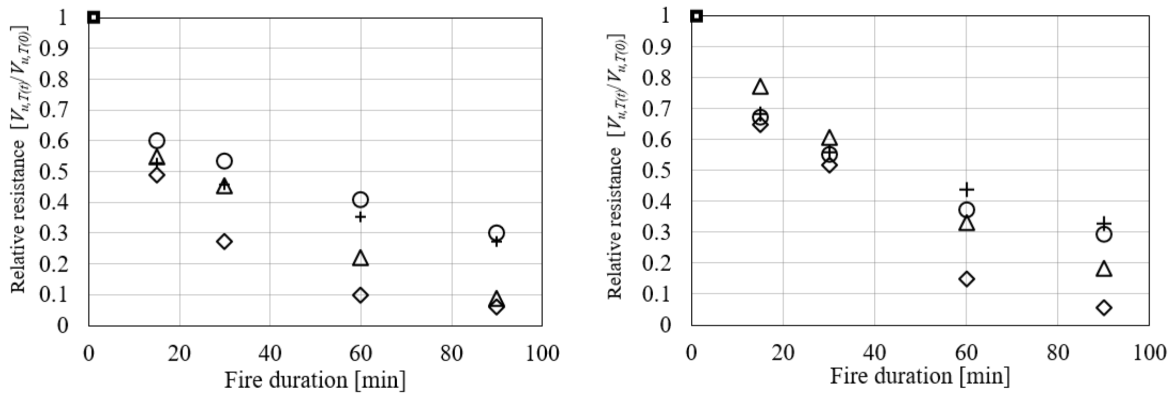


Fig. 7: Relative resistance as a function of fire duration for: (a) c_1 = 75 mm, h_{ef} =75 and d = 25 mm and (b) c_1 = 75 mm, h_{ef} = 95 und d = 25 mm

It can be seen that the design load (approx. 20% of the resistance at room temperature) leads to an additional reduction of the resistance after fire exposure. This applies to both, cold and warm condition. The influence increases significantly with longer exposure to fire and is more pronounced for the cold state. The reason for this is the fact that the preloading cause damage of concrete, which in interaction with the temperature-induced damage causes additional damage and consequently leads to additional reduction in the load-bearing capacity. The typical crack patterns (damage) after cooling of the specimen and loading until failure are shown in Fig. 8 for the cases with and without preloading. It can be seen that the preloading leads to pronounced damage and thus to a decrease in the load-bearing capacity after fire exposure.

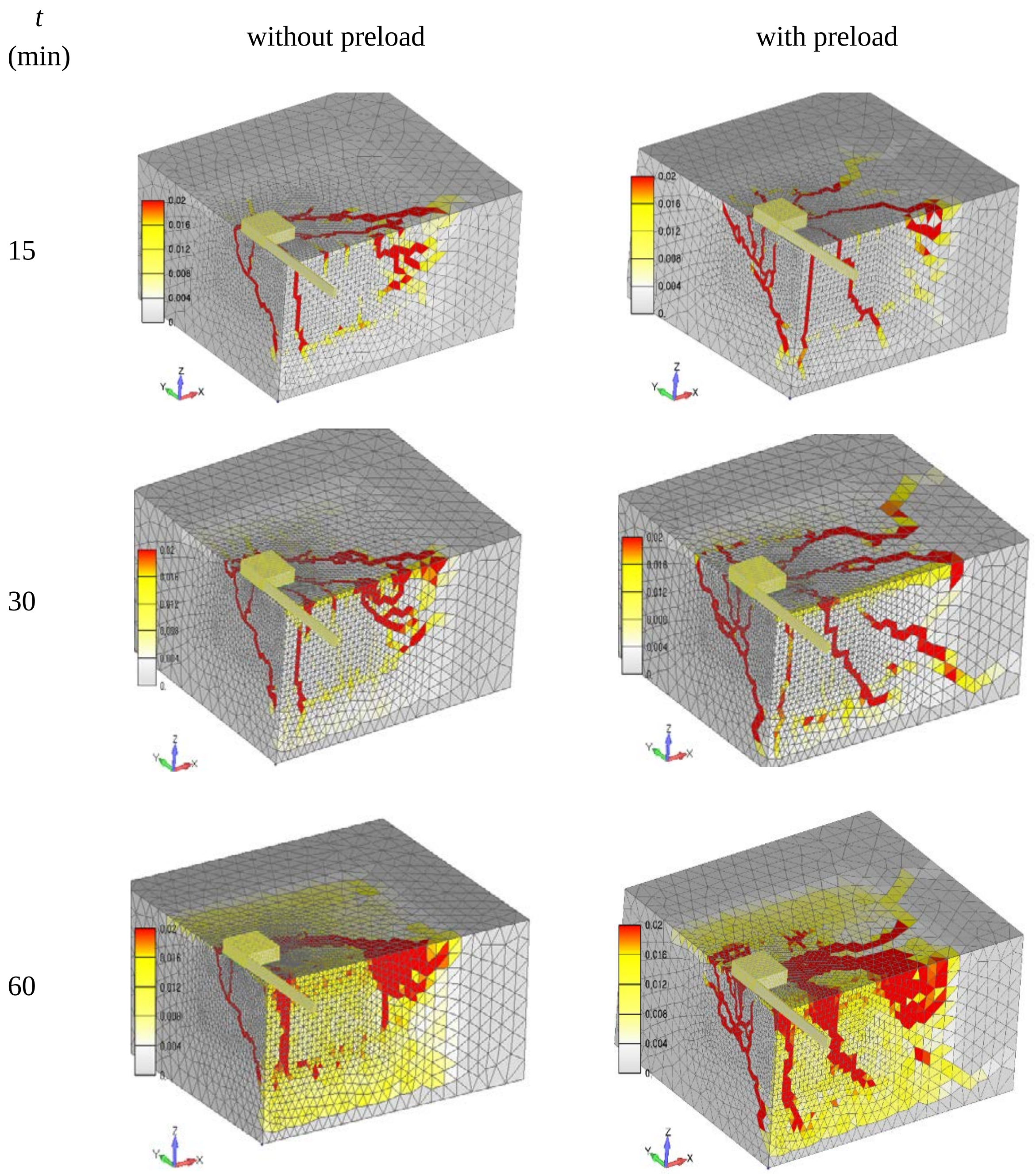


Fig. 8: Crack formation at the residual load in the cold state, with and without preloading

4. SUMMARY AND CONCLUSION

The purpose of the parametric study was to numerically investigate how the preloading of a single-headed stud anchor influence its shear load-bearing capacity after fire exposure. Based on the results of numerical simulations, the following can be concluded: (i) The employed 3D FE code based on the thermo-mechanical microplane model for concrete is able to realistically replicate the corresponding experimental tests; (ii) As expected, the simulation shows that with an increase of fire exposure time, the shear load capacity of the anchor decreases significantly. The decrease is more pronounced in the first 15 minutes of fire and greater for cold than for hot state; (iii) The results suggest that the preloading has a relatively strong influence on the shear load-bearing capacity of anchors. The reduction of resistance increases with increasing fire exposure time. The study indicates that for the fire exposure larger than 30 min there is a relatively high possibility that the resistance becomes smaller than the design load; (iv) The design formula for the shear resistance of fasteners should account for the influence of the preloading on the residual load-bearing capacity of anchors after fire.

REFERENCES

[1] ELIGEHAUSEN, R., MALLÉE, R., SILVA, J.F.: *Anchorage in concrete construction,* Berlin: Ernst & Sohn, 2006

[2] FUCHS, W., ELIGEHAUSEN, R., BREEN, J.E.: *Concrete capacity design (CCD) approach for fastening to concrete,* ACI Structural Journal J. 92, 73–94, 1995

[3] ANDERSON, N.S., MEINHEIT, D.F.: *Pryout capacity of cast-in headed stud anchors,* PCI Journal, 90–112, 2005

[4] KIM, J.S., JUNG, W.Y., KWON, M.H., JU, B.S.: *Performance evaluation of the post-installed anchor for sign structure in South Korea,* Construction and Building Materials, 44, 496–506, 2013

[5] GROSSER, P.R.: *Load-bearing behavior and design of anchorages subjected to shear and torsion loading in uncracked concrete,* PhD thesis, University of Stuttgart, Germany, 2012

[6] JEBARA, K., OŽBOLT, J., HOFMANN, J.: *Pryout failure capacity of single headed stud anchors,* Materials and Structures, 49, 1775–1792, 2016

[7] REICK, M.: *Brandverhalten von Befestigungen mit großem Randabstand in Beton bei zentrischer Zugbeanspruchung (Fire resistance of anchors far from an edge in concrete with axial loading)* (in German), PhD thesis, University of Stuttgart, 2001

[8] BAMONTE, P.F., GAMBAROVA, P.G., BRUNI, M., ROSSINI, L.: *Ultimate capacity of undercut fasteners installed in thermally-damaged high-performance concrete,* Proceedings of the 6th International Conference on Fracture Mechanics of Concrete and Concrete Structures, Catania, Italy, 2007

[9] PERIŠKIĆ, G.: *Entwicklung eines 3D thermo-hygro-mechanischen Modells für Beton unter Brandbeanspruchung und Anwendung auf Befestigungen unter Zuglasten (Development of a thermo-hydro-mechanical model for concrete under fire and application to fastenings loaded in tension)* (in German), University of Stuttgart, 2009

[10] TIAN, K., OŽBOLT, J., PERIŠKIĆ, G., HOFMANN, J.: *Concrete edge failure of single headed stud anchors exposed to fire and loaded in shear: Experimental and numerical study,* Fire Safety Journal, 100, 32–44, 2018a

[11] TIAN, K., OŽBOLT, J., SHARMA, A., HOFMANN, J.: *Experimental study on concrete edge failure of single headed stud anchors after fire exposure,* Fire Safety Journal, 96, 176–188, 2018b

[12] TIAN, K.: *Concrete failure of headed stud fasteners exposed to fire and loaded in shear: experimental and numerical study,* PhD thesis, University of Stuttgart, Germany, 2019

[13] OŽBOLT, J., LI, Y.-J. KOŽAR, I.: *Microplane model for concrete with relaxed kinematic constraint,* International Journal of Solids and Structures, 38, 2683-2711, 2001

[14] OŽBOLT, J., KOŽAR, I., ELIGEHAUSEN, R., PERIŠKIĆ, G.: *Three-dimensional FE analysis of headed stud anchors exposed to fire,* Computers and Concrete, 2, 249–266, 2005

[15] OŽBOLT, J., BOŠNJAK, J., PERIŠKIĆ, G., SHARMA, A.: *3D Numerical analysis of reinforced concrete beams exposed to elevated temperatures,* Engineering Structures, 58:166-174, 2014

[16] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION: *ISO 834-1 Fire Resistance Tests - Elements of Building Construction - Part 1: General Requirements,* Geneva, Switzerland, 1999

[17] BAŽANT, Z.P., OH, B.H.: *Crack band theory for fracture of concrete,* Materials and Structures, 16, 155–177, 1983

[18] EUROPEAN COMMITTEE FOR STANDARDIZATION: *FprEN 1992-4 Eurocode 2 Design of concrete structures* - *Part 4 Design of fastenings for use in concrete*, Brussels, Belgium, 2015